

# Rolls-Royce CLEEN II Program Overview



Brad Belcher

4 May 2021

CLEEN II Consortium Public Day, Virtual Meeting due to COVID-19 Pandemic

Export Control Information Table		
This document is subject to the following Export Control Information		
Country	Export Classification	Date
US	NO TECHNICAL DATA	4 May 2021, BDBelcher



## CLEEN II Technologies

CLEEN Technology Name	Goal Impact	Benefits and Application
Alternative Jet Fuel Test and Evaluation (Area A)	Alternative Fuels	Promote the development and introduction of viable, renewable alternative fuels to achieve the NextGen Air Transportation System goals
Advanced RQL Low NOx Combustion System	NOx Reduction	Demonstrate an RQL combustor with 65% reduced NOx relative to CAEP/8 limits
Boeing Short Nacelle Flight Demo	Weight and Drag Reduction	Verify characteristics in flight with angle of attack affects



# Flight Demo of Boeing Short Nacelle

## FAA CLEEN

- **Ground testing conducted under Boeing CLEEN II Contract**
  - Boeing baseline and short nacelles
  - Rolls-Royce Trent 1000 Engine
  - Testing at Rolls-Royce outdoor facility at NASA Stennis
  - Successfully completed to TRL 6
- **Follow-on flight testing under RRC CLEEN II Contract**
  - Testing moving to Rolls-Royce 747 Flying Test Bed to evaluate angle of attack effects to TRL 7
  - Flight scheduled for CY21 Q3





## Flight Test Plan and Preparation Status

### Hardware



- Boeing inlets and test engine at Rolls-Royce Tucson site.
- Final inlet and engine preparation activities on-going

### Paperwork



- Boeing safe-to-fly inputs received.
- Flight clearance activities on-going in the UK.
- Plan for completion of all paperwork in Jul 2021.

### Test



- Short Intake tests queued after current Trent 1000 maturity testing.
- Current plan is for short intake test slot to start in September 2021.
- Delivery of FAA CLEEN report planned before year end.





## Current status





# Rolls-Royce CLEEN II Sustainable Aviation Fuels

Brad Belcher

May 5, 2021

CLEEN II Consortium-Government and Public Day, Virtual



Jurisdiction	Export Control Classification (Rating)	Date
US	No Technical Data	4-19-2021 EBW

**Public Release No. V021031**  
**April 28, 2021**



## CLEEN Technologies

CLEEN Technology Name	Goal Impact	Benefits and Application
Alternative Jet Fuel Test and Evaluation (Area A)	Alternative Fuels	Promoted the development and introduction of viable, renewable alternative fuels to achieve the NextGen Air Transportation System goals. Data shared with the ASTM Aviation Fuel Community to support international approval of a fully synthetic jet fuel.





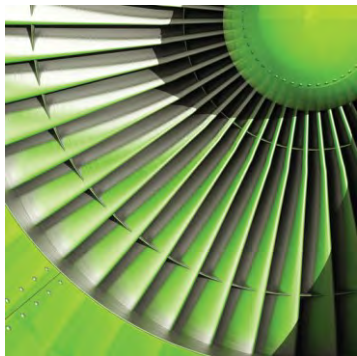
## Rolls-Royce Sustainable Aviation Fuel Program

### Elevator Speech

The Rolls-Royce Sustainable Aviation Fuel Program is complete and has promoted alternative jet fuel development, approval & deployment, which contributes to the attainment of FAA NextGen Air Transportation System goals. This robust evaluation program has characterized a novel fully-synthetic fuel's performance under representative engine conditions. This goal was accomplished through a series of "back-to-back" rig tests with conventional Jet A fuel, assessing the fuel's impact on combustor performance and emissions. Elastomeric seal performance was also assessed using the innovative Elastocon rig capability developed and demonstrated under CLEEN I. Data demonstrated the viability of 100% ATJ-SKA fuel for use in aviation. The data generated was compared to prior work, assessed, and shared with the ASTM Aviation Fuel Community in support of the International approval of a 100% Sustainable Aviation Fuel.



## Rolls-Royce Sustainable Aviation Fuel Program



istockphoto

## Accomplishments- Program Complete

- Promoted the development and introduction of a viable 100% sustainable fuel to meet NextGen Air Transportation system goals
- This robust evaluation program characterized a fully synthetic fuel's performance under representative engine conditions
  - Accomplished through a series of “back-to-back” rig tests with conventional Jet A fuel
  - Fuel chemistry/properties relationship upon fuel spray, combustor performance, operability, and emissions were tested
  - Elastomeric seal performance due to cyclic fuel switching under more realistic engine conditions was conducted
- Program demonstrated ATJ-SKA is a viable 100% SAF candidate for aviation use.
- The data generated supports the international approval of a fully synthetic jet fuel within ASTM Aviation Fuel Community
- Sustainable aviation fuel for aerospace gas turbine engine applications should provide reduced aerospace environmental impact and increased energy security



Fuel Selected

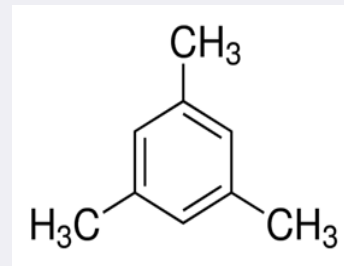
## “LanzaTech Alcohol to Jet Synthetic Kerosene with Aromatics”

87%

**Alcohol to Jet**



13%



**Mesitylene**

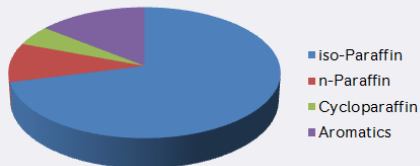
- ✓ Fully synthetic kerosene fuel- “ATJ-SKA”
- ✓ Allows for proper atomization and fuel system performance
- ✓ Acceptable combustion performance anticipated
- ✓ Acceptable elastomer seal performance

## Test Results

# Summary of ATJ-SKA Back to Back Test Results

- Laboratory characterization:
  - Primarily iso-paraffinic composition
  - Acceptable volatility, fluidity, and thermal stability
- Overall spray performance similar to Jet A fuel, with only minor differences noted
- Combustion flame tube:
  - Lean stability deteriorated slightly
  - Emissions – NO<sub>x</sub> similar, but CO and UHC emissions are higher at certain conditions, leading to lower combustion efficiency
  - Combustion liner wall temperatures are similar

**ATJ-SKA**



**Chemistry**



**Fuel Spray**



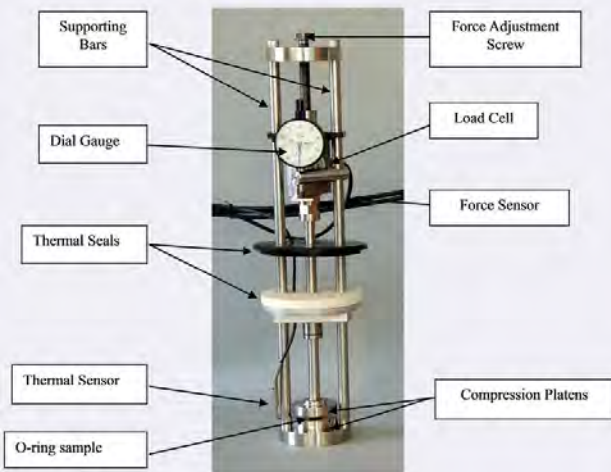
**Combustion**

No Technical Data

## Test Results

# Summary of Elastomeric Seal Testing

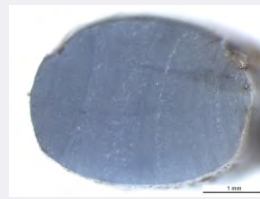
- Novel test method showed differentiation in representatively aged seal performance for 5 elastomer materials and 3 aromatic levels
- 30°C Testing Results:
  - Suggest sealing force 4% Aromatic ATJ < 13% Aromatic ATJ < Jet A-1
  - Minimum retained sealing force of ~10% still considered functional
- -40°C Cyclic Testing Results:
  - Sealing force dependent on temperature, but retained sealing force never reached zero for worst case (fluorosilicone)
  - Performance of highly degraded seals at low temperature considered poor, as expected
- Post-test seal condition consistent with stress relaxation data



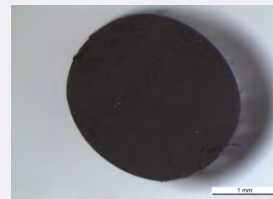
**Nitrile**



**Fluorosilicone**



**Fluorocarbon**



No Technical Data



## Sustainable Aviation Fuel Program

# Achievements

- **Completed Objectives:**
  - Laboratory and fit for purpose properties tested
  - Spray characterization performed
  - Elastocon compression stress relaxation data for five seal materials was obtained
  - Flame tube testing complete
  - Full technical report delivered
- **Wrapping up:**
  - Public technical report – due 3Q2021

Program has delivered objectives and is complete

# Sustainable Aviation Fuel Test and Evaluation

## Quad Chart



### Approach:

- Selected a suitable fully synthetic sustainable aviation fuel “ATJ-SKA”
- Evaluation accomplished through a series of “back-to-back” rig tests with conventional Jet A fuel
- Fuel chemistry/properties relationship upon fuel spray, combustor performance, operability, and emissions were tested
- Elastomeric seal performance due to cyclic fuel switching under more realistic engine conditions was conducted

### Accomplishments:

- Promoted the development and introduction of a viable 100% sustainable fuel to meet NextGen Air Transportation system goals
- This robust evaluation program characterized a fully synthetic fuel’s performance under representative engine conditions
- Evaluation demonstrated ATJ-SKA is a viable 100% SAF candidate.
- The data generated supports the international approval of a fully synthetic jet fuel within ASTM Aviation Fuel Community
- Sustainable aviation fuel for aerospace gas turbine engine applications should provide reduced aerospace environmental impact and increased energy security

### Program Status: COMPLETE

- Completed Objectives:
  - Laboratory and fit for purpose tested
  - Spray characterization performed
  - Elastocon compression stress relaxation data for five seal materials was obtained
  - Flame tube testing completed
  - Full technical report delivered
- Wrapping up:
  - Public technical report – due 3Q2021







# **Rolls-Royce CLEEN II**

## **Low Emission Combustion Technology**

Brad Belcher

5 May 2021

CLEENII Consortium Public Day

**Public Release No. V021032**

**April 28, 2021**



## CLEEN Technologies

CLEEN Technology Name	Goal Impact	Benefits and Application
Advanced RQL Low NOx Combustion System	NOx Reduction	Develop and demonstrate significant NOx reduction with advancing combustion technology that is suitable for emerging high pressure ratio, small core engines



## Rolls-Royce Low NOx Combustion Program

### Elevator Speech

The Rolls-Royce CLEENII Low NOx Combustor Program will advance the state-of-the-art in Rich-Quench-Lean (RQL) combustor performance, enabling significant reduction in NOx pollution for advanced engine platforms with aggressive turbine entry temperatures.

The comprehensive approach incorporates advanced fuel injection and wall cooling technologies coupled with implementation of enhanced mixing methodology.

A rigorous development plan with progressive validations through component rig and system level testing will mitigate risk and develop a combustion platform for engine evaluation.

We will build upon prior Rolls-Royce development to demonstrate emission reductions in two phases with a near-term configuration targeting NOx emission levels 40% below CAEP/8 limits and a final configuration with NOx level 65% below CAEP/8.



## Rolls-Royce Low NO<sub>x</sub> Combustion Program

### Program Objectives

- Define cycle efficiency improvement and emissions reduction technologies that work together in future engine architectures to provide significant contributions toward the CLEEN II goals
- Develop RQL combustion technology capabilities through the application of advanced technologies, new design methods, research of fundamental principles
- Demonstrate through component and full-scale system testing LTO NO<sub>x</sub> emissions 65% below CAEP/8 requirements, while limiting or reducing other gaseous and particle emissions
- Conduct TRL6 engine testing to demonstrate viability for next generation production application and fleet engine retrofit opportunities



## Rolls-Royce Low NOx Combustion Program

# Program Approach

## **Integrate low emission enabling technologies in Rich-Quench-Lean (RQL) combustion system**

- Innovative fuel injection to improve uniformity and dispersion
- Novel mixing aerodynamics to minimize NOx formation
- Advanced wall cooling to improve cooling effectiveness
- Optimized combustor shape to reduce residence time

## **Conduct progressive development and demonstration of combustor performance**

- Combustion design guided by high fidelity CFD analysis
- TRL3 rigs used for component technology development
- TRL5 rigs used to demonstrate system performance
- Engine testing to demonstrate integration and viability in the engine environment (TRL6).
- Phased approach to incorporate prior results and lessons-learned into ultimate low-NOx configuration.



## Overall program time line

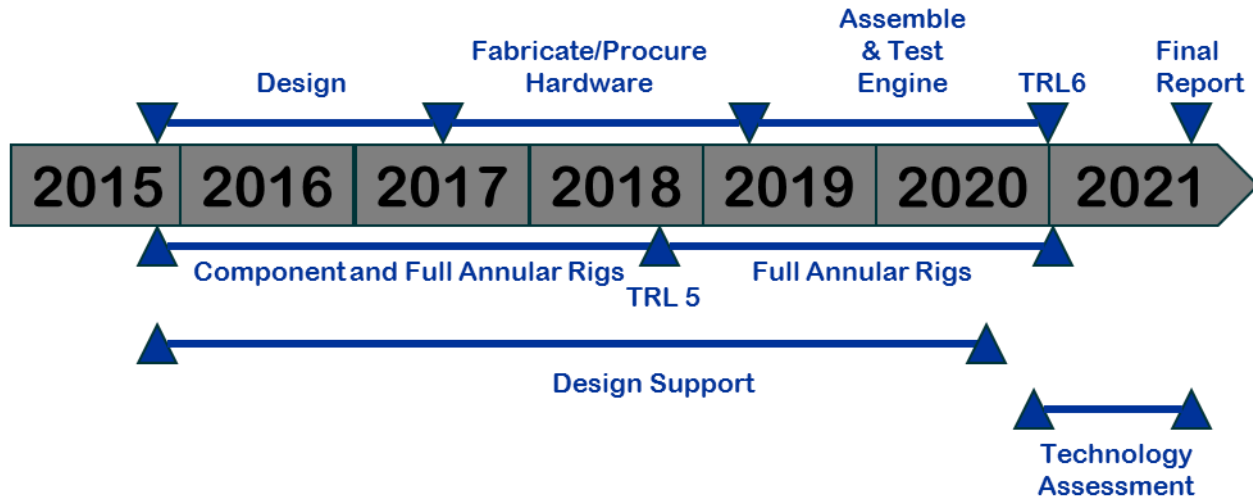
### Rolls-Royce Low NOx Combustion Program

Program launched in  
October 2015

Component rig testing  
(TRL3) in 2016-17 used to  
inform combustor design

Full annular rig testing  
(TRL5) of designs began  
in 2018

Engine testing (TRL6)  
initiated in late 2019



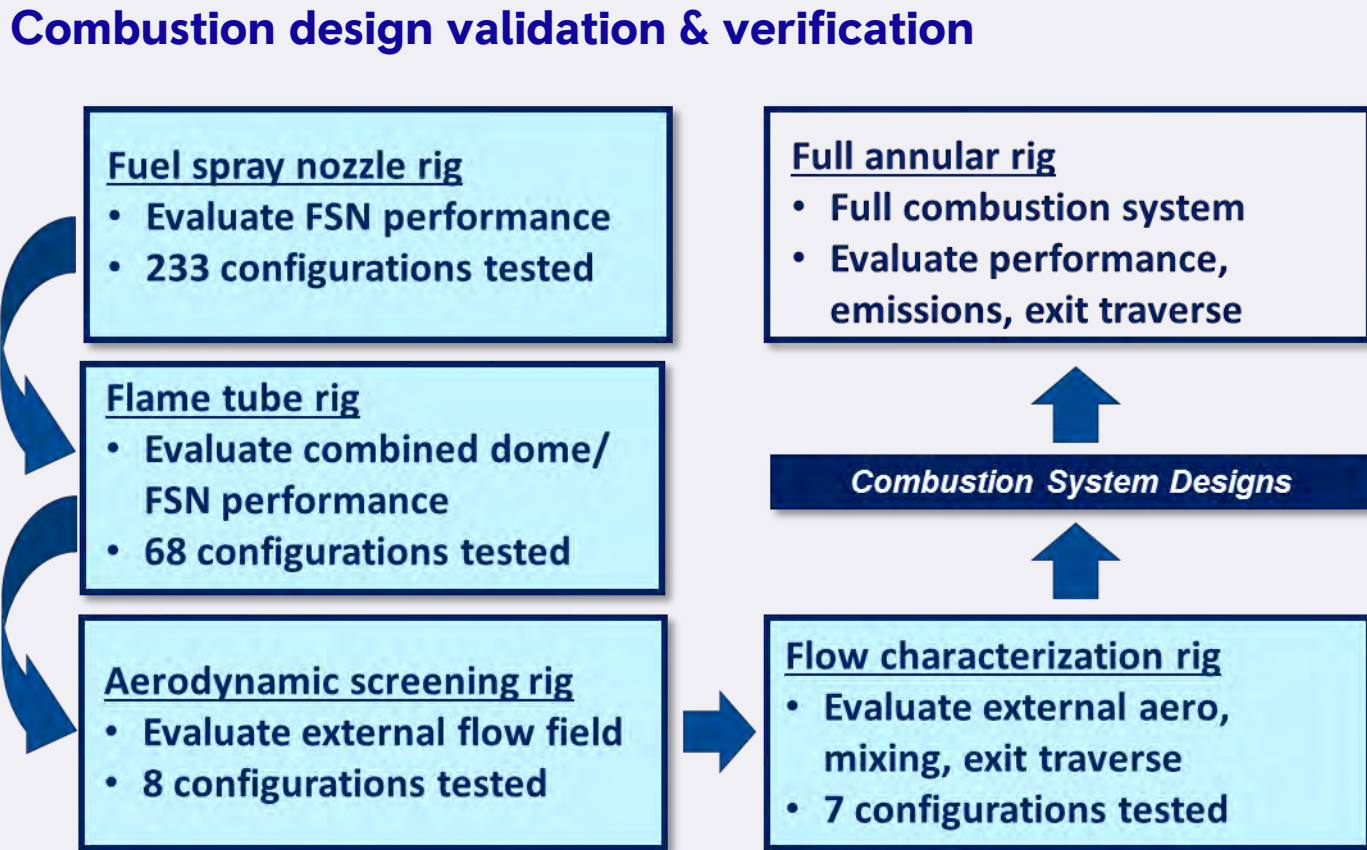
**Final phase of program is now underway**





## Rolls-Royce Low NO<sub>x</sub> Combustion Program

Progressive validation  
via component and  
system rigs to inform  
designs and down-  
select configurations



**Full annular rig testing informs engine test readiness**

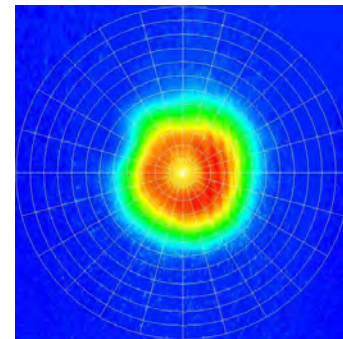
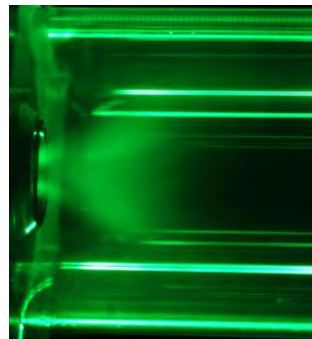


# TRL3 Activities to Characterize Fuel Injector and Assess Combustion Performance

## Rolls-Royce Low NO<sub>x</sub> Combustion Program

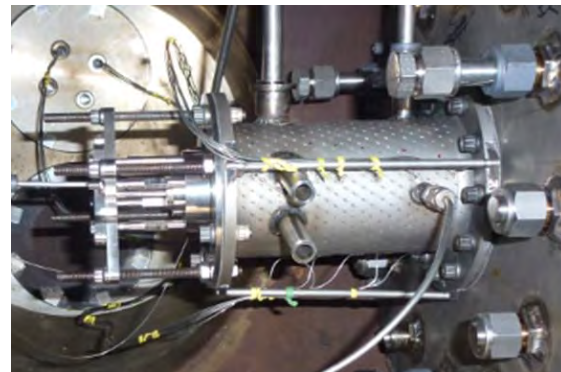
### Fuel Spray Diagnostics

- Fuel spray quality
- Liquid droplet dispersion
- Transient spray effects
- Spray visualization



### Single Sector Flametube

- High inlet temperature and moderate pressures
- Emissions
- Operability
- Flexibility to assess multiple concepts





## Rolls-Royce Low NOx Combustion Program

### Full Annular Combustor Rig

- Key objectives to characterize combustor exit temperatures, wall temperatures, emissions and operability
- Features rotating emission and temperature probes to map the combustor exit
- Maintains comprehensive aerodynamic similarity to the engine design
- Provides combustion system level performance validation prior to installation into demo engine



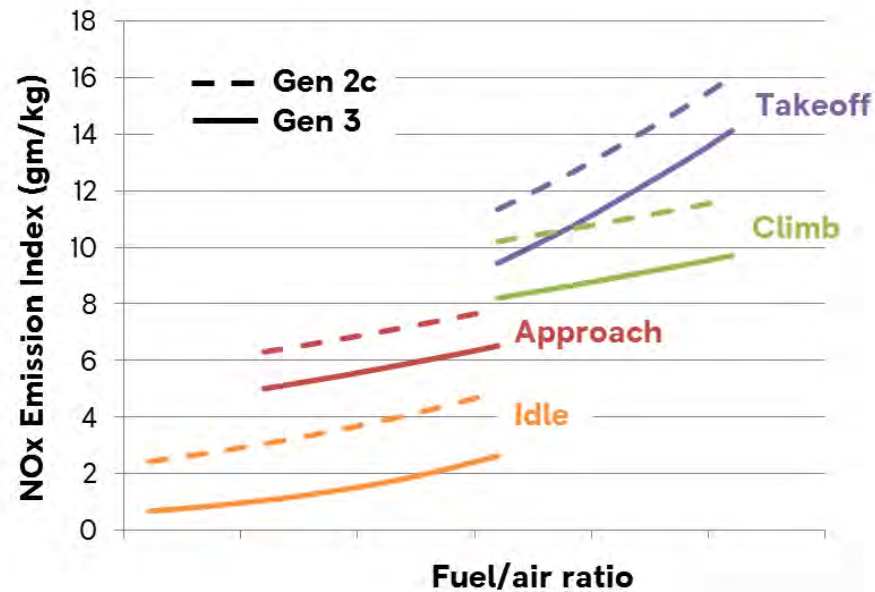


## Rolls-Royce Low NOx Combustion Program

### Past 18 Month Achievements

#### Full annular rig test program was completed

- Conducted test of final CLEEN II configuration
- Lower NOx emissions than prior designs at all operating points
- CLEEN II goal of 65% margin to CAEP8 was demonstrated



#### Engine demonstration testing of the combustion system was completed

- Combustor met all engine test objectives – confirmed TRL6

### Low NOx Combustion program has achieved CLEEN II goals



## Rolls-Royce Low NOx Combustion Program

## Future Project Plans

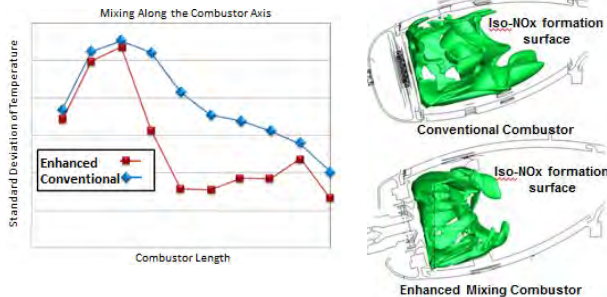
### **CLEEN II combustor program is now complete**

- Final report will be published in 2021



## Advanced RQL Low NOx Combustion System

### Quad Chart



### Anticipated Benefits:

- Significant NOx reduction
- Negligible operability impact
- Highly cost effective
- Technology capable of broad product insertion
- Advanced wall cooling and manufacturing technology

### Risks/Mitigation Plans:

- Rigs are planned to manage risk and provide
  - Analysis benchmarking
  - Component and system development

### Objectives:

- Demonstrate LTO NOx emissions 65% below CAEP/8 requirements, while limiting or reducing other gaseous and particle emissions
- Conduct TRL6 engine testing to demonstrate viability for next generation production application and fleet engine retrofit opportunities

### Work Statement:

- Integrate low emission enabling technologies in a Rich-Quench-Lean (RQL) combustion system and develop and demonstrate low emission performance

### Accomplishments / Milestones:

- Conducted detailed fuel spray diagnostics (TRL2)
- Completed array of single sector flame tube tests (TRL3)
- Full scale testing (TRL5) of small core combustions to validate performance
- System integration and testing (TRL6) through small core demonstrator engine
- Attainment of 65% NOx margin to CAEP8 .

### Schedule:

